EFFICIENT CONCEPTS FOR LARGE ERECTABLE SPACE STRUCTURES

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EFFICIENT CONCEPTS FOR LARGE ERECTABLE SPACE STRUCTURES

(Figure 1)

The development of credible concepts for large space structures requires design information on structures of unprecedented proportions. The Langley Research Center has initiated studies of basic generic concepts for large space structural elements in order to provide meaningful standards for evaluating competing types of construction, to ensure that the unique behavior aspects of large lightweight members are not overlooked in design, and to provide experimental and analytical data on promising concepts.

In the present paper, the status of LaRC development of the nestable column concept will be reviewed including results of member and truss component tests, and planned assembly studies. In addition, more recent studies of alternative member concepts will be presented. Preliminary results on relative efficiency of several types of truss-type columns will be compared and future test plans will be discussed.

EFFICIENT CONCEPTS FOR LARGE ERECTABLE SPACE STRUCTURES

PURPOSE OF GENERIC CONCEPT STUDIES

- ESTABLISH STANDARDS TO COMPARE COMPETING CONSTRUCTIONS
- CONFIRM METHODS OF DESIGN FOR LARGE, LIGHTWEIGHT MEMBERS
- PROVIDE DATA ON PROMISING CONCEPTS

STATUS OF LaRC STUDIES

NESTABLE COLUMNS

- MEMBER TESTS
- TRUSS COMPONENT TESTS
- ASSEMBLY STUDIES

ALTERNATE CONCEPTS

- EFFICIENCY STUDIES
- FUTURE TESTS

Figure 1

NESTABLE COLUMN CONCEPT

(Figure 2)

The nestable tapered column concept combines a structurally efficient wall configuration with a simple concept to achieve high packaging efficiency. The wall configuration is a hollow tapered tubular section made largely from unidirectional graphite to give the column low axial expansion and good mass/buckling strength characteristics for compression loadings. High packing density is achieved by using half-column tapered sections and nesting them like paper cups for transportation into orbit. Previous studies (ref. 1 and 2) have shown that cost-efficient weight critical payloads can be achieved in the Space Shuttle Transportation System. On orbit, the columns may be assembled and used as building blocks in large space truss structures (e.g. ref. 3).

The figure illustrates some five-meter graphite-epoxy columns with aluminum center and end joints. The elements were designed and constructed to evaluate the practicality of lightly loaded (1000 lb.) members.

REFERENCES

1. Bush, H. G.; and Mikulas, M. M., Jr.: A Nestable Tapered Column Concept for Large Space Structures. NASA TMX-73927. July, 1976.
2. Bush, H. G.; and Mikulas, M. M., Jr.: Some Design Considerations for Large Space Structures. AIAA Paper No. 77-395, March 21-23, 1977.
3. Mikulas, M. M., Jr.; Bush, H. G.; and Card, M. F.: Structural Stiffness, Strength and Dynamic Characteristics of Large Tetrahedral Space Truss Structures. NASA TMX-74001,

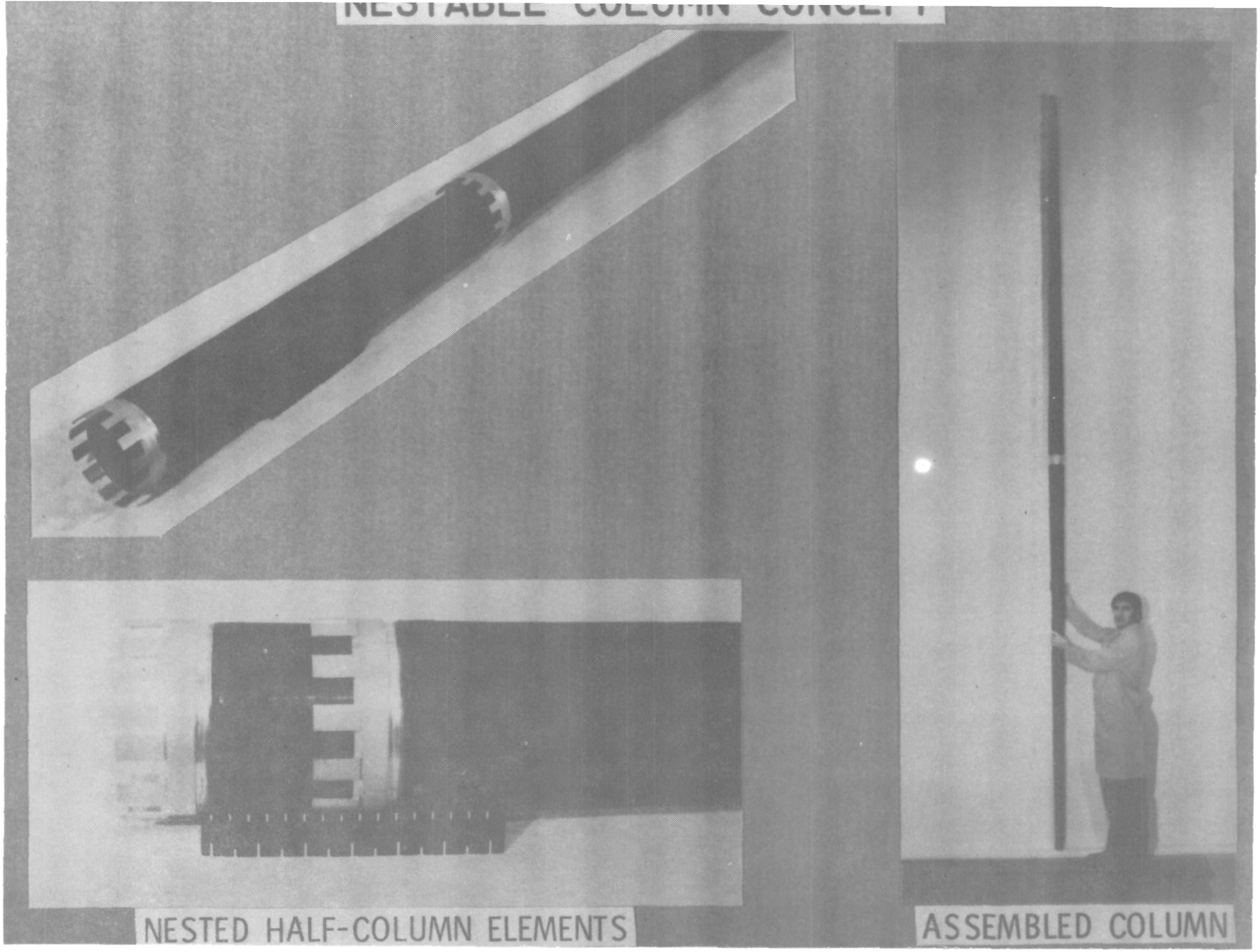
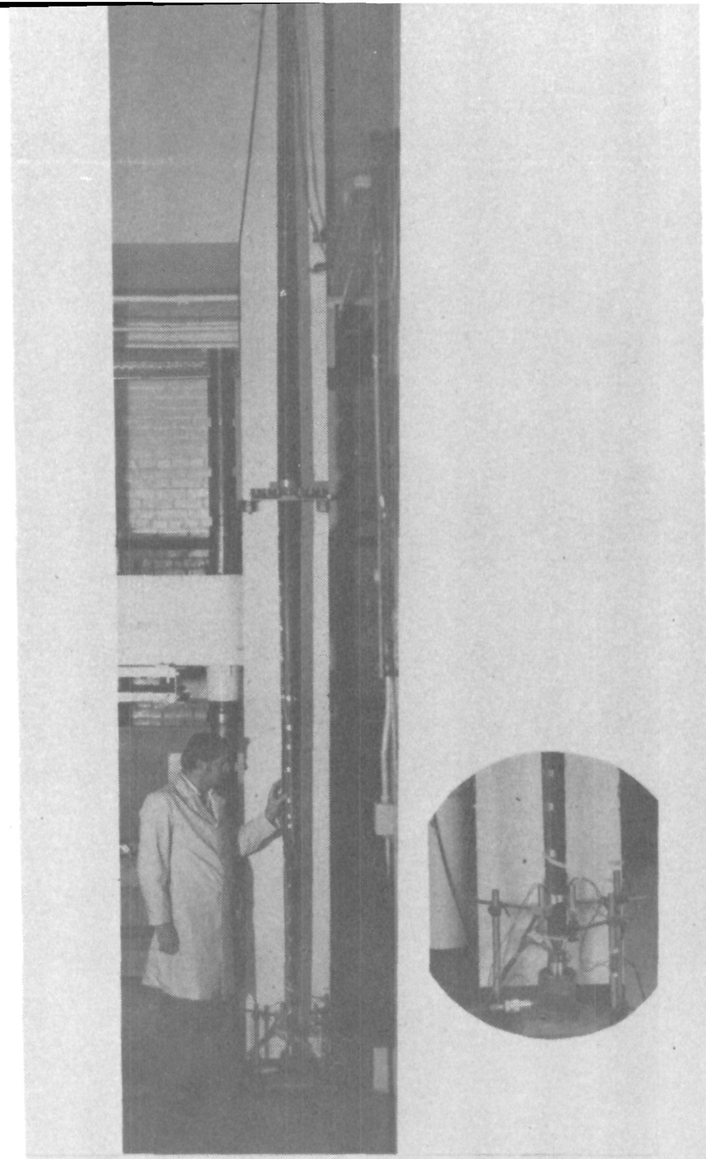


Figure 2

5-METER NESTABLE COLUMN BUCKLING TESTS

(Figure 3)

In order to verify the behavior of long slender nestable columns, a series of column buckling tests were conducted with 5.2-meter-long graphite-epoxy specimens mounted vertically as shown in the figure. Simple support end conditions were achieved by the use of ball-and-cup end fittings. Of interest in the tests was low-strain material behavior ($\varepsilon < .0005$), repeatability of tests, and behavior of the interlocking leaf-spring center joint under load.



5 METER NESTABLE COLUMN BUCKLING TEST

Figure 3

GRAPHITE NESTABLE COLUMN BUCKLING TEST RESULTS
(Figure 4)

As summarized in the Table, seven columns were tested. As indicated, the column walls were nearly unidirectional (0° fibers alined with loading direction) with 90° surface plies. Also shown on the Table are values of measured deviation from straightness in terms of the amplitude of maximum lateral deviations δ and the column length ℓ. The low values of both the initial imperfection amplitudes and buckling load permitted the columns to be buckled repeatedly without damage with repeatable test results.

In comparing test buckling results with analysis, it was discovered that some test articles were made with overlaps in 0° plies causing significant increases in thickness. The changes from nominal extensional stiffness are shown in the Table. By correcting thicknesses of the analysis model, excellent agreement was obtained between experimental buckling loads $P_{cr_{exp}}$ and theoretical loads $P_{cr_{th}}$ based on Timoshenko tapered column theory.

BUCKLING TEST RESULTS

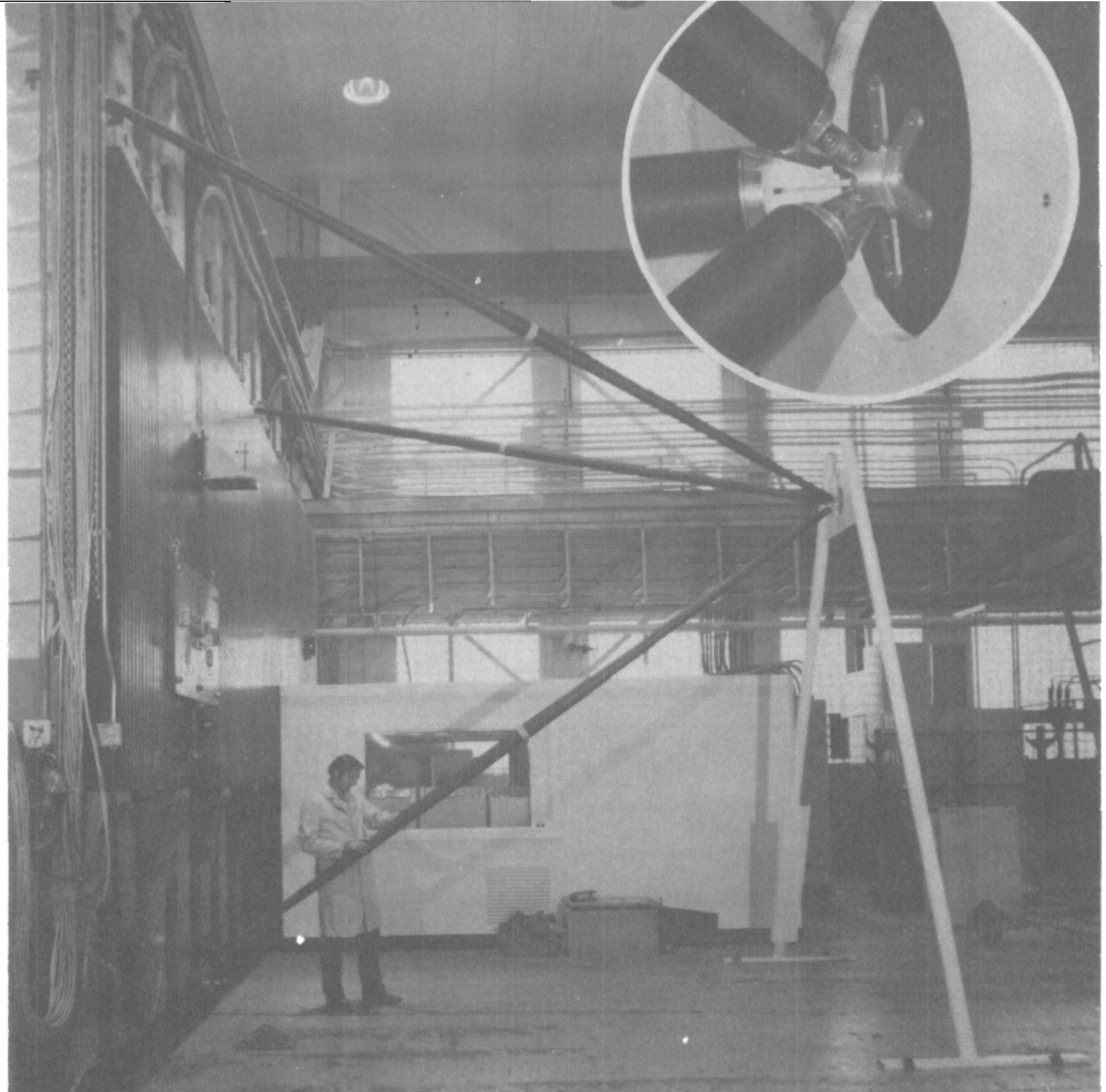
TEST SPECIMEN	LAYUP	$\frac{\delta}{L}$	$\frac{(Et)_{exp.}}{(Et)_{nom.}}$	$\frac{P_{exp.}}{{}^{*}P_{th.}}$
1	$90/0_3/90$	.0009	.939	.990
2	$90/0_4/90$	0	.964	.988
3		-	1.074	.996
4		-	1.063	1.000
5		.0004	1.088	1.003
6		.0007	1.074	.997
7		.0004	1.075	1.017

* TIMOSHENKO TAPERED COLUMN WITH CORRECTED STIFFNESS

Figure 4

TRIPOD BUCKLING TESTS
(Figure 5)

In addition to the column tests, three of the tubes were assembled into a tripod as shown in the photograph. Loads were applied to the apex of the tripod in a plane parallel to the base. Of interest in these tests was the behavior of the aluminum cluster joint at the tripod apex.



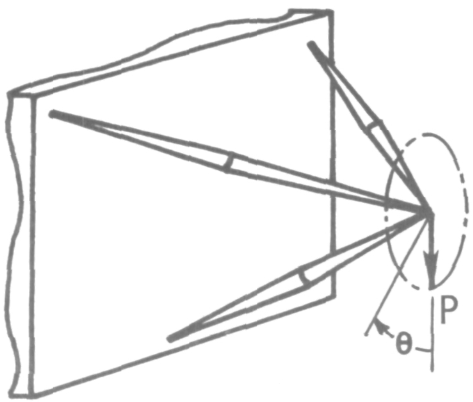
TRIPOD BUCKLING TEST

Figure 5

TRIPOD BUCKLING TEST RESULTS
(Figure 6)

Buckling results are summarized in the Table for three values of the loading angle Θ. A series of buckling calculations with various boundary conditions were made using a finite element code (SPAR). As suggested, test results are bounded by simple support and simple support-clamped boundary conditions. Using the test data for $\Theta = 0°$ and previous test data for simply supported columns, buckling loads were estimated to be about 1.27 times loads obtained from the tripod analysis with simply supported boundaries. As the Table indicates, this method gives reasonable estimates for $\Theta = 30°$ and $\Theta = 60°$ test results as well.

TRIPOD BUCKLING TEST RESULTS



$$\frac{P_{exp}}{P_{th}^{*}}$$

θ^0	SIMPLE SUPPORT CLUSTER AND BASE	SIMPLE SUPPORT CLUSTER, CLAMPED BASE	ELASTIC** BOUNDARIES
0	1.309	.837	1.035
30	1.342	.858	1.061
60	1.171	.749	.926

*SPAR FINITE ELEMENT MODEL (12 ELEMENT BEAMS)

**ELASTIC SUPPORT FACTOR OF 1.27 X SIMPLE SUPPORT (ESTIMATED FROM COLUMN TESTS AND $\theta = 0^0$ TEST RESULTS)

Figure 6

VIBRATION TEST RESULTS
(Figure 7)

Limited surveys were made of the vibration behavior of the columns and the assembled tripods using a low force shaker and a lightweight movable accelerometer. A 23 kg tip mass was attached to the tripod cluster joint to help discriminate between individual tripod member frequencies. In the Table, values of the lower bending frequencies are compared with theoretical predictions. Column test results were compared with a shell-of-revolution analysis which accounted for aluminum end fittings and abrupt changes in thickness. Experimental results were within ± 5% of theoretical predictions. Tripod test results were compared with finite-element predictions (SPAR) using the same model as used for buckling. The model employed simply supported base supports and a simply supported apex with a point tip mass. Experimental results deviated by a maximum of 8% from theory.

COLUMN TESTS

TEST SPECIMEN	BOUNDARY CONDITIONS	MODE	$\frac{f_{exp}}{f_{th}^{*}}$
1	FREE - FREE	1ST BENDING	.95
		2ND BENDING	.95
		3RD BENDING	.95
1	SIMPLY SUPPORTED	1ST BENDING	.97
		2ND BENDING	.96
2	SIMPLY SUPPORTED	1ST BENDING	1.04
		2ND BENDING	1.05

TRIPOD TESTS

5	TRIPOD WITH BASE FIXTURES, CLUSTER JOINT AND TIP MASS	1ST BENDING	.92
6		1ST BENDING	.93
7		1ST BENDING	.93

* SHELL OF REVOLUTION ANALYSIS FOR COLUMNS;
SPAR FINITE ELEMENT ANALYSIS FOR TRIPOD

Figure 7

36-ELEMENT OCTETRUSS TEST
(Figure 8)

As part of further evaluation of nestable columns as components of large space trusses, the multi-element truss section shown is scheduled for tests at LaRC this summer. The section shown is a small representative module of the so-called tetrahedron truss or octetruss which has been investigated in previous studies. As suggested, the truss will be cantilevered from a sturdy backstop and loaded with a tipload. Of particular interest here, is the behavior of the 9-element joint shown in the top face of the truss. The truss will be subjected to bending load to induce column buckling and a vibration survey will be conducted.

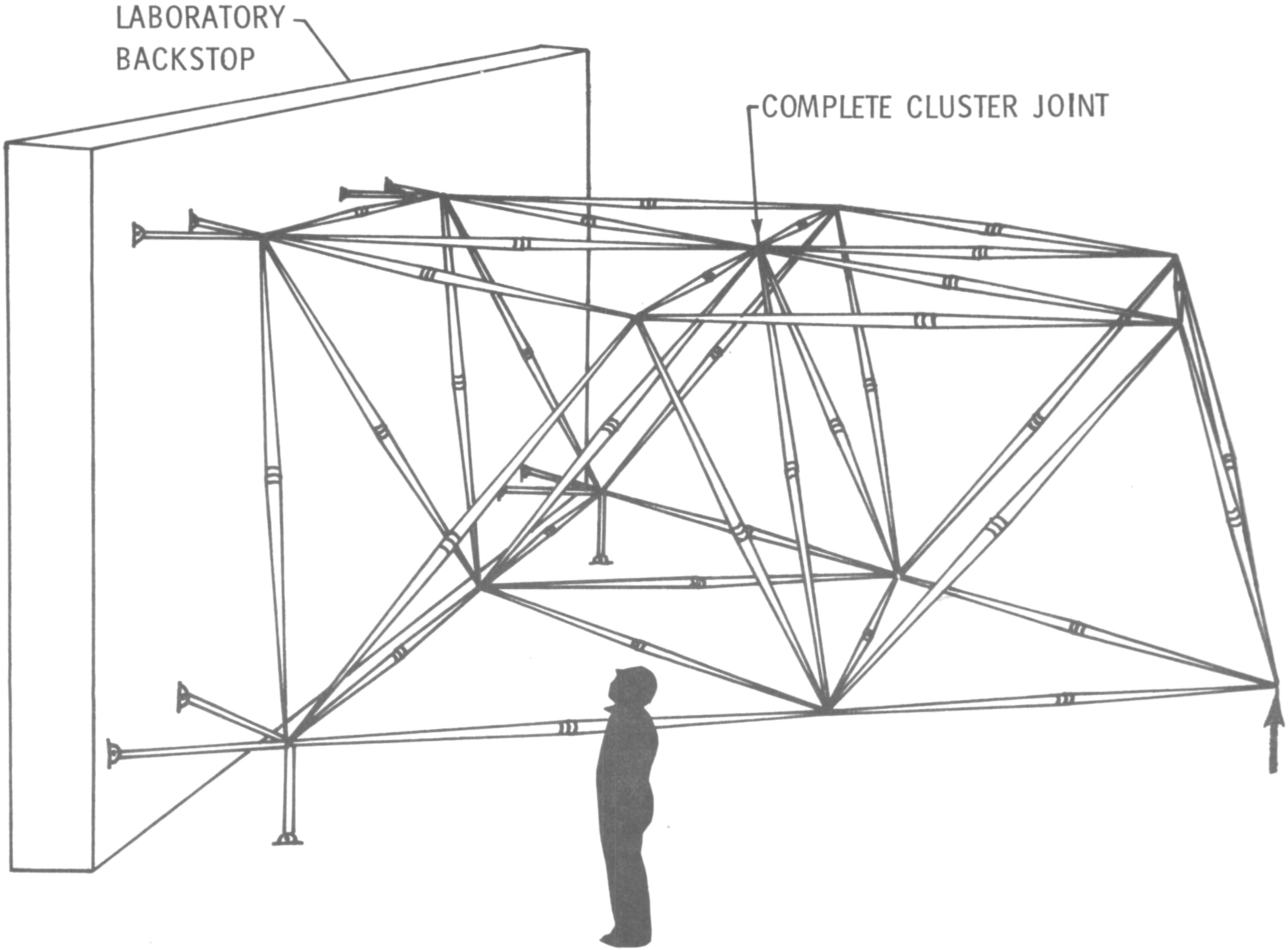
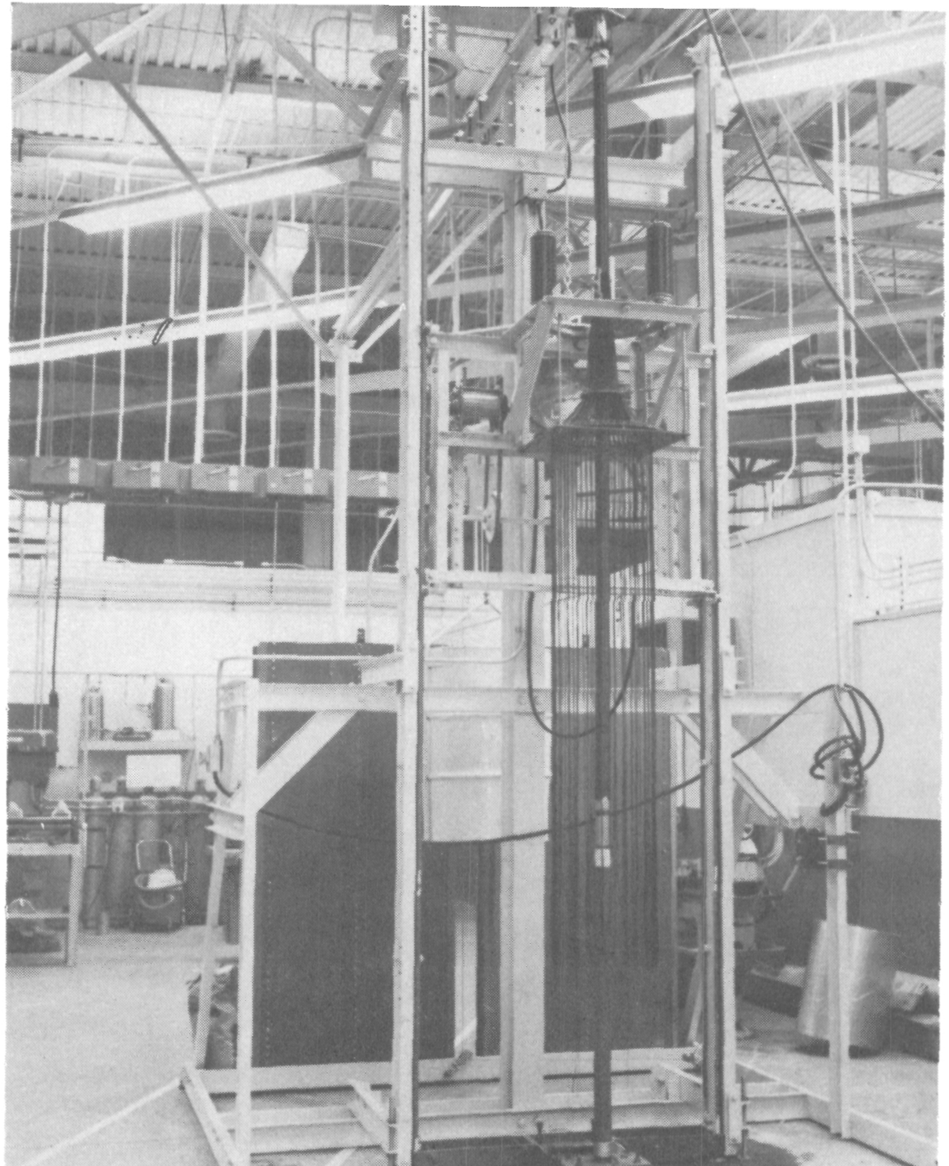


Figure 8

MANUFACTURING FACILITY FOR OCTETRUSS ELEMENTS
(Figure 9)

As part of efforts to reduce costs of nestable column truss members, a manufacturing facility is being developed by Lockheed. The photo shows a tube-stand facility suitable for making half columns up to 5 meters in length. The heart of the facility is a movable platform on which is mounted spools (near top of photo) for circumferential winding and a gathering ring and tension plate for laying 0° degree filaments. The tension plate is perforated with small guide holes containing ceramic rollers which can be tensioned against the filament.

To initiate the tube manufacturing of a 90-0-90 configuration, a tapered mandrel is first placed in the stand. Then a single upward winding pass from bottom to top of the mandrel is made to form the inner surface circumferential ply. The tube is then completed with a single downward pass of the movable platform in which the tensioned 0 degree filaments are fed through the tension plate and gathering ring, then overwound with the external 90° ply. Either film or painted resin can be used in the process and tubes may be bagged and cured in place.



MANUFACTURING FACILITY FOR OCTETRUSS ELEMENTS

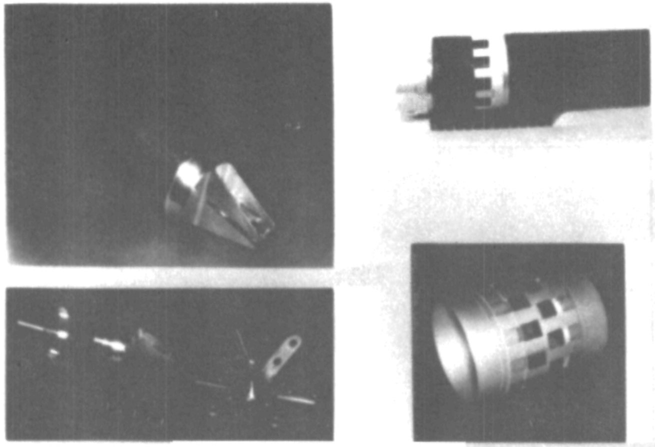
Figure 9

ASSEMBLY TECHNOLOGY
(Figure 10)

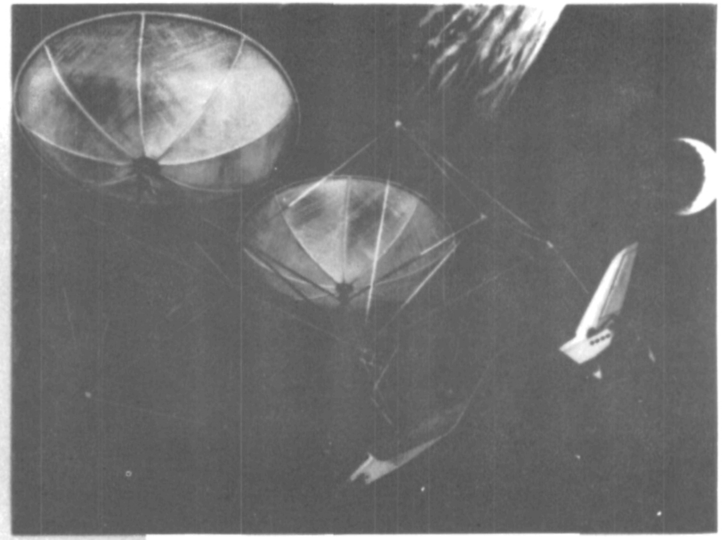
The final step in the development of the nestable column concept is the invention of a credible automated assembly process. Our studies of joint concepts suggest that assembly concepts will strongly dictate the most suitable center and end joints for a member. Preliminary studies have been performed by Rockwell International on the feasibility of using a modified shuttle Remote Manipulator System to erect a large antenna platform using nestable columns. More recently Lockheed has suggested that automatic erector system based on a lightweight translating parallelogram fixture might be feasible. Preliminary estimates of space truss assembly times suggest a reasonable potential for the automated erector, but there are great uncertainties in the realism of assembly time predictions.

It appears that there is a serious need for in-depth investigations of competing assembly concepts. In view of the range of complexities and costs of such systems, it would seem prudent to first establish baseline manned assembly timelines for early shuttle assembly activities. Furthermore, assembly times of automated devices should be established by laboratory tests of scaled erectors. In Phase One of the Large Space Systems Technology Program, such in-depth studies are planned.

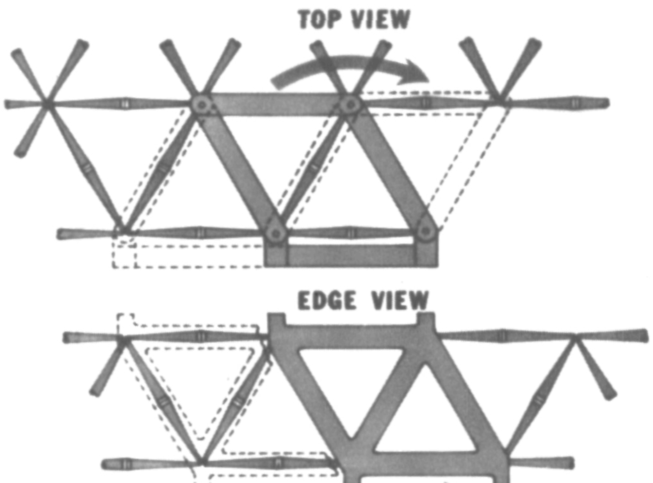
ASSEMBLY TECHNOLOGY



JOINT CONCEPTS



SHUTTLE - RMS ASSEMBLY



AUTOMATIC ERECTOR CONCEPT

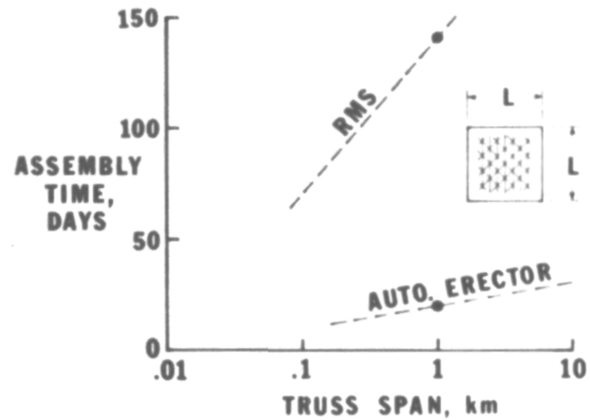


Figure 10

DESIGN STUDIES ON ALTERNATE CONCEPTS
(Figure 11)

The chart shows the three main aspects of LaRC investigations of alternative concepts to the nestable column. In the design of very long, lightly loaded column members, concepts such as the tri-element truss column and columns with central compression posts stabilized with pretensioned wires look promising. Such concepts are effective because they overcome structural efficiency limitations posed by minimum gauge solid-skin structures. Generic studies of the relative weights and efficient proportions of such members are underway.

An aspect that is under investigation is a method of simplifying relative efficiency comparisons in regions where minimum gauge structure is predominant. Classical efficiency comparisons have used the mass parameters $\frac{W}{L^3}$ and a loading index $\frac{P}{L^2}$. In the minimum gauge regime, families of curves of constant length are awkward to compare. An example of a simplified efficiency chart will be discussed subsequently.

A final aspect of the LaRC design studies is the effect of initial imperfections (i.e. deviation from straightness) on column structural buckling strength. Recent work suggests that highly optimized structures are particularly sensitive to relatively small amplitude imperfections.

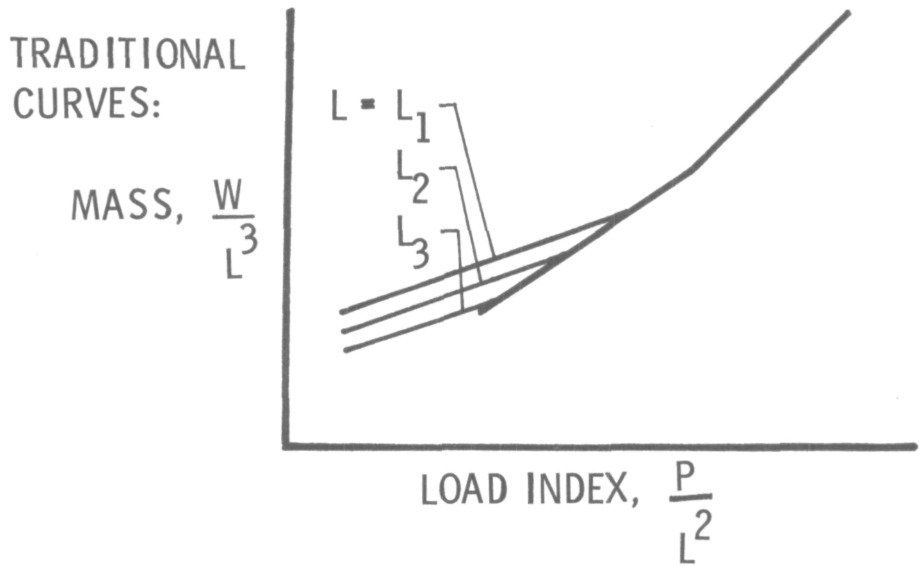
DESIGN STUDIES ON ALTERNATE CONCEPTS

- STUDYING CONFIGURATIONS MORE APPROPRIATE FOR ULTRA LARGE STRUCTURES

  (1) TRI - ELEMENT TRUSS - COLUMNS

  (2) TENSION - STABILIZED COLUMNS

- REDEFINING MASS/LOADING INDEXES TO SIMPLIFY MASS ESTIMATES IN LIGHTLY LOADED REGIME



- INVESTIGATING EFFECTS OF INITIAL IMPERFECTIONS

Figure 11

MASS-STRENGTH CHARACTERISTICS OF GRAPHITE-EPOXY COMPRESSION COLUMNS
(Figure 12)

The figure shows a preliminary comparison of the relative weights of three types of graphite-epoxy column construction. The parameters are column mass normalized as $\frac{W}{\ell^{5/3}}$ (W = weight, ℓ = length) and the applied compressive load P. Efficiency curves are shown for; 1) minimum gauge graphite hollow tubular construction (t = .015in.) (representative of the nestable column construction ignoring the effects of taper), 2) tri-element truss construction with solid longerons and 3) tri-element truss construction with hollow tubing longerons. As expected, the curves shown illustrate the superiority of open-construction over solid tubing for the lower loads.

For tri-element truss construction with solid tube longerons, a representative design point for a 50m foldable astromast is shown and is in agreement with the computed curve. A data point for a General Dynamics design of a manufactured-in-space tri-element truss beam is also shown; it is somewhat higher than predicted curves because of open rather than closed construction of the column longerons. Finally a data point is shown for a Boeing design for Solar Satellite Power Station member. The point illustrates that gigantic columns with longerons made from nestable column subelements possess high efficiency.

MASS/STRENGTH CURVES FOR Gr/E COMPRESSION COLUMNS

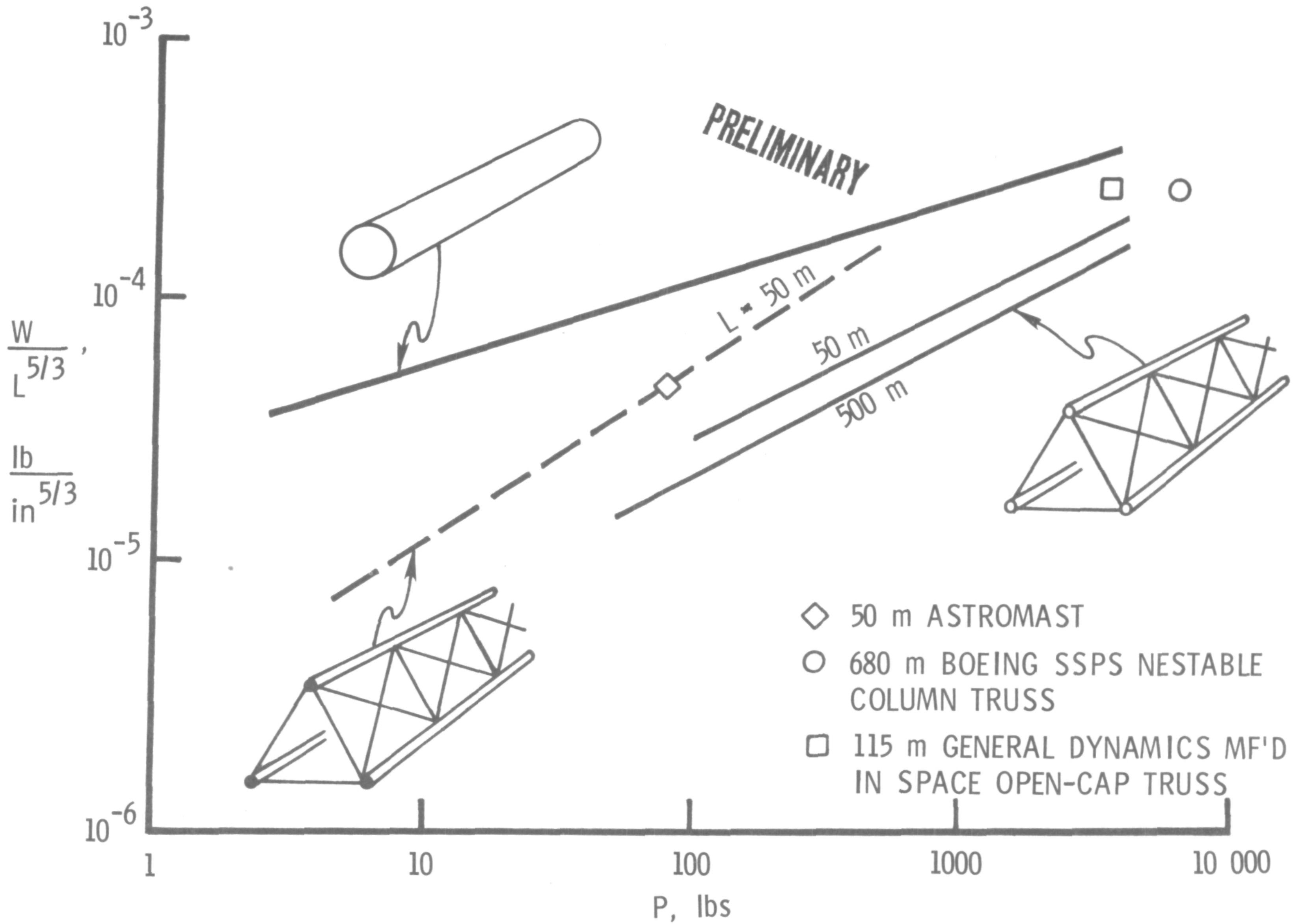


Figure 12

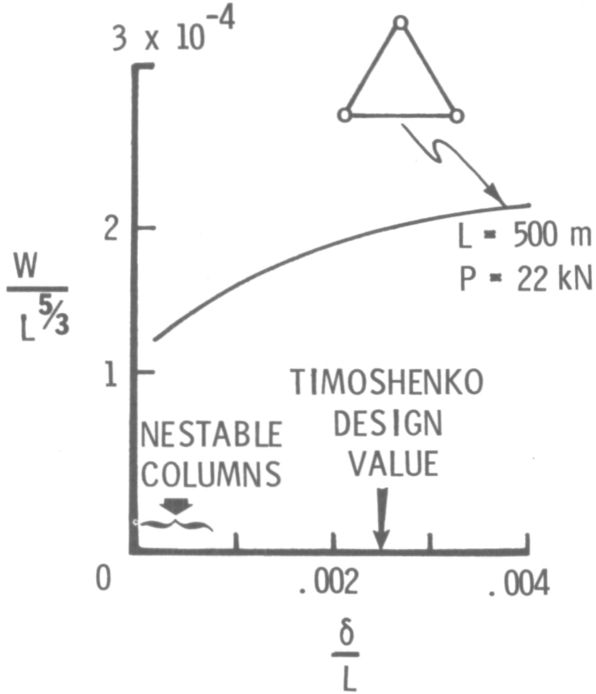
EFFECTS OF INITIAL IMPERFECTIONS
(Figure 13)

Although tri-element truss columns look very attractive from a mass-efficiency point of view, preliminary studies suggest that the members are sensitive to the effects of imperfections. The left-hand curve shows an example of the increase in mass needed to make an imperfect column carry the same load as a perfectly straight member. A typical recommended design value is shown for the imperfection amplitude $\frac{\delta}{\ell}$ as well as the values obtained from tests of the 5 meter nestable columns. If the recommended value is used, a factor of two in weight increase is required to develop the same load carried by a perfectly straight member. Also shown are values of imperfection measured on the nestable columns which suggest the recommended design value (developed in 1930's) could be overly conservative.

A second difficulty with columns with large imperfections is suggested in the right-hand figure. For the recommended imperfection design value, a nondimensionalized load-shortening curve is shown. The curve indicates that for possible operational loads in the column (say limit load with a safety factor of 1.5, $\frac{P}{P_E} = .67$), large nonlinear behavior is evident.

EFFECTS OF INITIAL IMPERFECTIONS

WEIGHT PENALTY



NONLINEAR STRESS - STRAIN CURVE

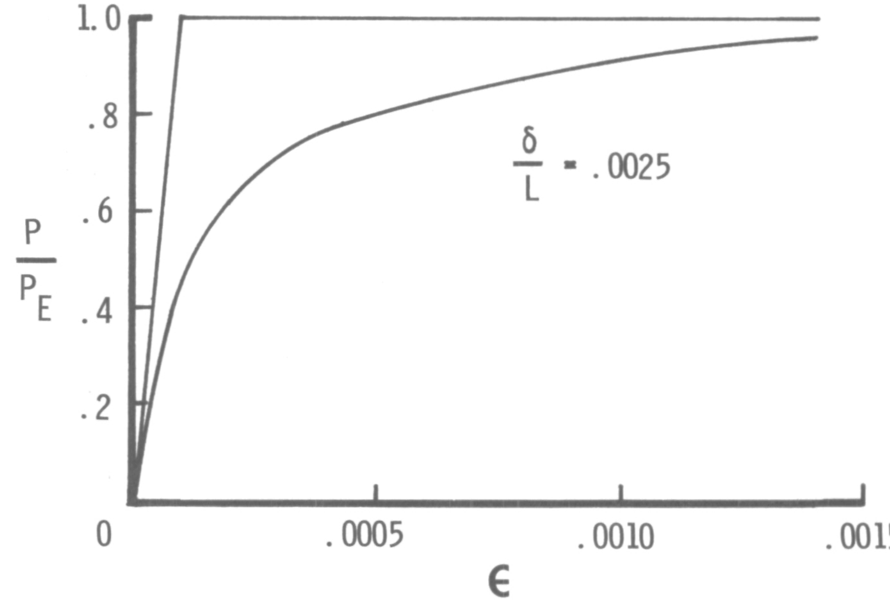


Figure 13

LATTICE COLUMN TESTS IN STRUCTURAL DYNAMICS RESEARCH LABORATORY
(Figure 14)

In order to obtain experimental data on the strength and imperfection behavior of very large members, a test facility is being developed in the Langley Dynamics Research Laboratory. In this building, a large tower capable of accomodating members up to 25 meters in length will be modified for vibration and buckling tests as suggested in the figure. A short section of a sturdy aluminum lattice (tri-element truss) column has been designed and tested to verify detail design. A 24-meter column is presently under construction at Langley and should be ready for test in late spring. Plans call for a series of tests of at least two types of competing construction.

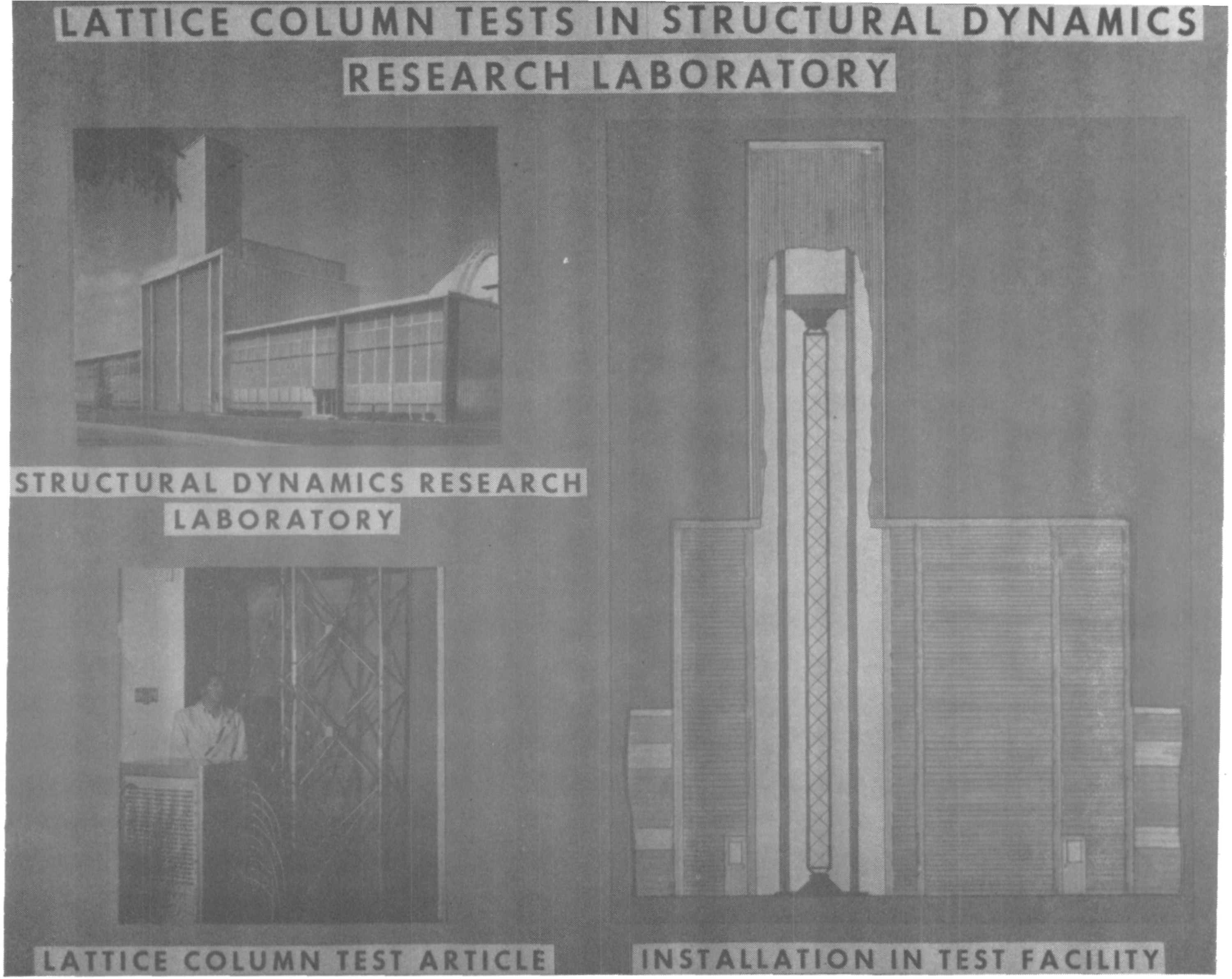

LATTICE COLUMN TESTS IN STRUCTURAL DYNAMICS RESEARCH LABORATORY
STRUCTURAL DYNAMICS RESEARCH LABORATORY
LATTICE COLUMN TEST ARTICLE
INSTALLATION IN TEST FACILITY

Figure 14